

Textile materials and structures for wound care products

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Abstract: A thorough understanding of the healing mechanism and dressing requirements for different types of wound repair is necessary before optimum products based on textiles could be engineered. In this chapter, first a general overview of the wounds and their healing, and of the available dressings and bandages, is presented. This is followed by a detailed discussion of the polymer and fiber materials of which the dressings are composed and of the textile processes that are used in forming the wound care products.

Key words: wounds, wound healing strategies, dressings, bandages, dressing polymers and fibers, textile processes.

3.1 Introduction

In a human's fast-paced life, characterized by external hazards and physiological neglects, physical injury of one or the other form is a commonly encountered event. It must be attended to in order to protect body health, function and appearance. The primary procedure used is the application of a dressing, which, in the main, protects the site against external assaults and aids in generating the needed physiological environment for efficient repair. The dressing can be as simple as a strip of plain textile, or as complex as an engineered composite that contains layers of different geometries and reactive materials, including medicines. The type of dressing depends on the type and the condition of the wound. Wound repair may be simple and inconsequential and performed by the patient itself or it may be complex enough to warrant surgery and hospitalization. An effective treatment requires a thorough understanding of wound types and healing mechanisms and knowledge of the interventions that are available and would ideally assist in the repair process.

A major increase in the understanding of the requirements for a dressing emerged in the 1970s when the pioneering work of Winter¹ showed that the wounds healed faster and more satisfactorily if the environment at the site was kept moist. Until then, the primary function of a dressing was

considered as one or more of absorbing the exudate, keeping the wound dry, and protecting it against external pathogens as well as further injury. The structure was also required to be comfortable. With the progress already made in terms of the understanding of the healing steps and requirements for different types of wounds, a wide variety of dressings are now available.

A minor wound may be defined as one that is not chronic and also not seriously acute. However, if not attended to properly, the same wound could become infected, enlarged and acute enough to require advanced dressing and medical procedure. The first line of treatment of a minor wound is a passive dressing, which is product that is textile in origin and may be made by a weaving, knitting or non-woven process. The dressing can also be a solid film, cast directly from a polymer. If there is bleeding and the potential for swelling, a bandage may be required in conjunction with absorbent gauze in order to exert transverse pressure and control both hemorrhage and edema. Like the passive dressings, the bandages are also primarily textile structures that are made by one of the fabric-forming technologies.

In this chapter, after a general review of wounds, healing, and dressing requirements, a brief description of the various types of dressings and the bandages available to choose from is given. A more in-depth coverage of some of the advanced dressings, touched on in the chapter, can, however, be found in other chapters of the book. In the second half of this chapter, a detailed discussion of the fiber materials and the textile structures used in producing the dressing and bandage products is presented.

3.2 The role of wound dressings

Skin is the largest organ of the body and has multiple components and, therefore, functions: the epidermis, which is the outer layer and composed of dead cells, is hydrophobic and responsible for protecting against the environment;² the dermis, or the middle layer, which is made up of living cells with a network of blood vessels and nerves, is responsible for registering external stimulus, i.e. touch/feel, and thermal regulation of the enclosed body; and the subcutaneous layer, which is mainly made up of fat, is responsible for insulating the body against shock. The cells on the surface are constantly replaced by those below, causing the top layer to slough off. The repair of an epithelial wound then is essentially a scaling up of this process by the use of interventions. Much has been learnt during the past half a century about wounds, the healing process and the nature of the products required to successfully treat the lesion. A wet environment, composed of isotonic saline and wound fluids, has been shown experimentally to be most favorable for rapid healing of wounds. The inflammatory and proliferative phases of dermal repair in healing are also accelerated.³

It was realized that bacteria did not generate in the wound but were acquired from an external source; thus simply washing with soap and water alleviated much of the risk of infection. Use of a protective covering formulated the simple but effective aseptic means for the treatment.

An essential part of any wound management is wound dressing, important considerations for which are the extent to which it restricts evaporation of water from the wound surface, buffers pain and trauma, manages exudates and protects against bacterial invasion. Although wound healing which is the stated part of a wound management protocol has been described in recorded history, our understanding of its basic principles has grown more in the past half century than in the preceding two millennia.⁴ The recent outstanding growth in our knowledge about healing is highly promising and has already led to introduction of new and exciting concepts, novel therapeutic modalities, and innovative wound management products. As new materials are discovered, new dressings emerge which promise to play an active role in modifying healing of all types of wounds.^{5,6}

As the products become more sophisticated, they also tend to become more 'wound-specific'. In order to select an optimum treatment for a wound and for different stages during healing, it is important that we understand the types of wounds we encounter, the sequence of events that take place during repair, and the treatment options we have available to choose from.

3.3 Categorization of wounds

Wounds have been categorized in many different ways, but they all reflect commonly the differences in the required treatment, and the expected time and prospects of healing. The classification of wounds recognizes the type of injury (blunt contusion, sharp laceration, thermal, chemical, etc.), the extent of tissue loss, and the presence of infection, foreign bodies, and underlying structural injuries (fracture of bone, exposure of vital parts such as tendons and blood vessels). A general classification of wounds is as follows:

1. Wounds with no tissue loss.
2. Wounds with tissue loss. This generally includes three types of wounds; those that are
 - (a) caused by burning, trauma or abrasion;
 - (b) the result of secondary events involving chronic ailments, as, for example, venous stasis, diabetic ulcers, and pressure sores; or
 - (c) induced as a part of the treatment of the wound itself, as, for example, the wound arising at the donor site for skin grafting, or the wound due to derma-abrasion.

From the standpoint of the extent of injury, a wound may also be classified in terms of the layers involved:

1. The superficial wounds, involving only the epidermis.
2. The partial thickness wounds, involving also the dermis.
3. The full thickness wounds, involving, additionally, the subcutaneous fat or deeper tissue.

Most wounds can also be broadly characterized as acute and chronic. In the former type, that may or may not have tissue loss, healing tends to proceed through a timely and orderly reparative process. In the chronic wounds, on the other hand, healing has failed to proceed through this process or it has proceeded without establishing a sustainable anatomical and functional result. The chronic wounds are classically subdivided into venous stasis ulcers, pressure ulcers, and diabetic ulcers. To a lesser extent, the traumatic wound with extensive cutaneous loss that has not been replaced for some reasons also may fall in the category of chronic wounds.^{4,7}

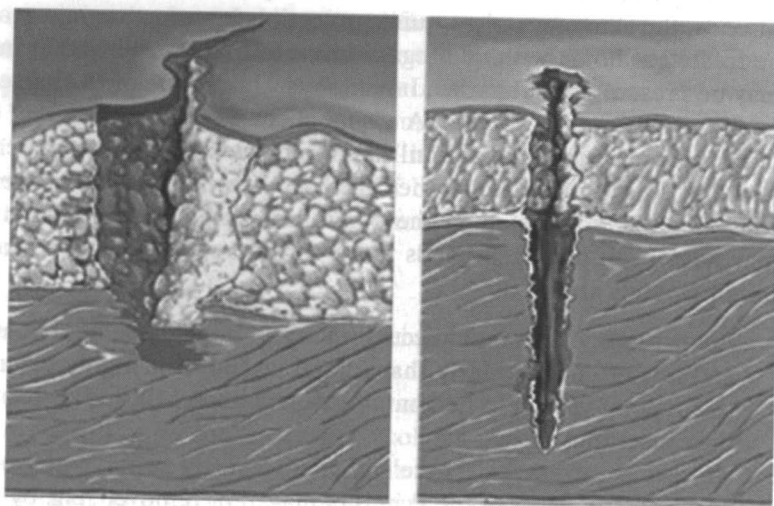
3.4 Minor wounds

A wound that has no tissue loss and is not chronic can be classified as minor with high prospects of healing with minimum scarring. Minor wounds often occur as the result of unanticipated trauma and may include injuries, such as lacerations, abrasions and blisters, and more serious wounds such as skin tears and bites. In many instances, such as superficial wounds, the skin may only require protection from further injury and can be treated at home with due regard given to the possibility that infection may be present or could arise. Infection is usually one of the biggest risks for minor traumatic wounds. A visual check for the presence of foreign material, its removal and careful cleansing may precede the application of a wound dressing. If, on the other hand, the wound is deep, as for example caused by penetration, then the possibility that an underlying structure may have been damaged needs to be considered. Some of the causes of minor wounds are:⁸

- *Lacerations.* This wound occurs when soft body tissue has become torn and it is often irregularly shaped and jagged. It is highly common for this type of wound to be contaminated with debris and or bacteria by the object that caused it.
- *Abrasions or grazes.* These are more exactly superficial wounds in which the top layer of the skin is damaged or removed, e.g. by the skin sliding across a rough surface. Small blood vessels may become visible and bleed. These injuries often contain dirt and gravel. Abrasions are

considered the most common type of wound, and perhaps the least dangerous.⁹

- **Blisters.** These are usually the result of friction between the top two layers of the skin. Puncturing the blister, draining the fluid and removing the top layer often allow the area to heal more quickly. In many cases, the blister will burst of its own accord. In both instances, a protective dressing is required.
- **Cut (incision).** Such wounds usually have clean edges which are the result of surgery, or injury caused by a sharp-edged object. Since blood vessels are cut straight across, there can be profuse bleeding. Among all types of wounds, incisions are the least likely to become infected, because the abundance of flowing blood serves to protect against pathogens finding their way in.
- **Puncture.** A puncture wound typically occurs when the skin is pierced by a cylindrical object such as a needle or a nail. These wounds can be dangerous as one cannot easily identify the depth to which the puncture has reached; they can be particularly dangerous if the wound is located on the abdomen or thorax.⁹ With this type of wound, bleeding will occur, in a similar way to the wound caused by a knife. Figure 3.1 depicts the difference between a laceration and a puncture wound.¹⁰
- **Penetration.** A penetration is a type of puncture but the damage is deeper such as it happens when a knife or bullet enters the body.
- **Bites.** These may be human or animal and are of special concern, especially if caused by an animal, as bacteria from the mouth can enter and



(a)

(b)

3.1 Wound types: a) laceration, b) puncture.⁹

- result in an increased risk of tetanus and infection. Most animal bites are sustained from pets, usually dogs, and can cause abrasions, deep scratches, and lacerations as well as puncture wounds. Cat bites are considered more serious due to the high incidence of infection.

3.4.1 General treatment strategy for minor wounds

Cleaning the wound and the surrounding skin is usually the first stage in treating a minor wound. This step removes debris and other foreign material which, if left, could cause infection. *Abrasions* require thorough irrigation as dirt is frequently embedded in the ruptured skin. An antiseptic solution may be used to cleanse the wound. Clean *surgical wounds* that have been sutured simply require the cleaning of old blood before the application of a dry dressing. In some cases it may be necessary to debride the wound before proceeding; in others, repair to underlying structures may need to be addressed before applying a dressing.

Wounds greater than 6–8 h old have an increased risk of infection. In all cases of traumatic injuries, the patient's tetanus status needs to be assessed for coverage. Following this, an assessment of the wound in terms of the location, size and depth and any additional trauma to the underlying structures needs to be determined. Animal bites need to be monitored for 24–48 h for signs of infection.

After thorough cleansing and assessment, a choice of dressing is then made, which may be a simple low-adherent or an advanced multi-layer composite to not only protect the wound but also to absorb blood or exudates and keep the wound moist. A detailed discussion of dressings is given later in this chapter.

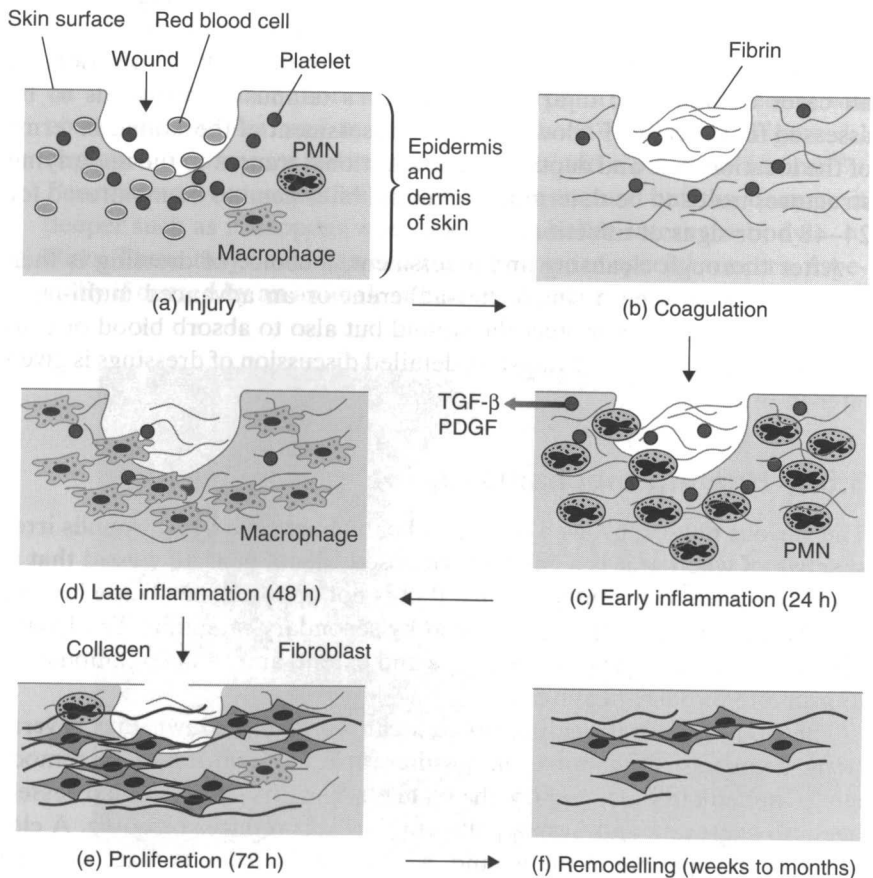
3.5 Healing mechanisms

The various phases involved in wound healing are seen in all wounds irrespective of whether it is a carefully opposed, clean, incised, wound that is healed by primary intention or one that is not opposed, has tissue loss, or is infected and exuding and is healed by secondary intention. The length of each phase varies with wound type and extent, and can be manipulated to promote or delay healing.

The body's natural healing process can be broken down into several steps: hemostasis, inflammation, proliferation, and maturation or remodeling. Immediately after injury, the platelets from the severed blood vessels begin to aggregate and form a platelet plug. This reduces bleeding. A clot forms in the opening of the wound, which dehydrates in contact with the air and forms a scab. In the second phase, neutrophils, monocytes and macrophages emerge, which tend to demolish or debride any devitalized

tissue and foreign bodies present, such as bacteria. The phagocytes act to clear debris and destroy the ingested material.¹¹ In the third stage, new vessels are formed which carry the oxygenated blood to the site bed. The fibroblast cells lay down a network of collagen fibers surrounding the neo-vasculature of the wound. In the final stage, the process of remodeling of the collagen fibers laid down in the proliferation phase occurs, and this may take a long time (Fig. 3.2).¹² A problem arises in the last steps of the healing process for large or cavity wounds as the body is not able to completely seal the site with a scab-like formation. The cavity must be plugged with an appropriate dressing to assist in the process.

Depending on the type of wound, healing treatment is considered to be by one of three processes: primary, secondary, or tertiary (often called delayed primary).⁶ Healing by primary intention occurs in most surgical



3.2 Phases of cutaneous wound healing (a) injury, (b) coagulation, (c) early inflammation (24 h), (d) late inflammation (48 h), (e) proliferation (72 h), (f) remodelling (weeks to months).¹²

wounds in which the edges have been adequately approximated. Such wounds are usually clean and heal rapidly. Large wounds with significant tissue loss are allowed to heal by secondary intention. Such wounds are often encountered following massive trauma, surgical ablation of large tumors, or deep burns. Tertiary or, more appropriately, delayed primary healing is induced by reconstruction using skin grafts or flaps. Tissue gaps and poorly approximated edges will ultimately heal by secondary intention accomplished by re-epithelialization from the wound edges and mostly by wound contraction. Clearly, primary or delayed primary wound healings are by far preferable and superior to secondary healing.

3.6 Wound dressings

3.6.1 Historical

The history of surgical wound management indicates how, with research and understanding of wounds and their healing, dressings have evolved over time and set the criteria for the design of new and better dressings and effective wound management. Until the research by Winter¹ which illustrated the benefits of a moist environment for healing in the second half of the twentieth century, relatively few advances had taken place in wound care management. Since the early nineteenth century, advances in wound treatment occurred largely due to experience gained in military surgery. These observations brought out the benefits of a sterile environment in healing and led to clean and sterile gauze replacing the non-sterile products. In 1880, Joseph Gamgee developed the famous composite dressing consisting of absorbent cotton or rayon fiber enclosed in a retaining sleeve.¹³ The dressings used were sometimes medicated with iodine or phenol. Gauzes impregnated with paraffin were introduced as non-adherent dressings for the treatment of burns and other similar wounds. Medicated versions of these, the so-called 'tulle gras' were subsequently introduced and some of these are still being used. The work of Winter led to the development of a whole range of new dressings: films, gels, foams, polysaccharide materials and chitosan. These have revolutionized the treatment of wounds of all types. Some of the requirements for ideal wound dressing mentioned are:¹⁴⁻¹⁷

1. Absorbing exudates and toxic components from the wounds surface
2. Maintaining a high humidity at the wound/dressing interface
3. Allowing gaseous exchange
4. Providing thermal insulation
5. Protecting the wound from bacterial penetration
6. Being non-toxic
7. Easily removable without causing trauma to the wound.

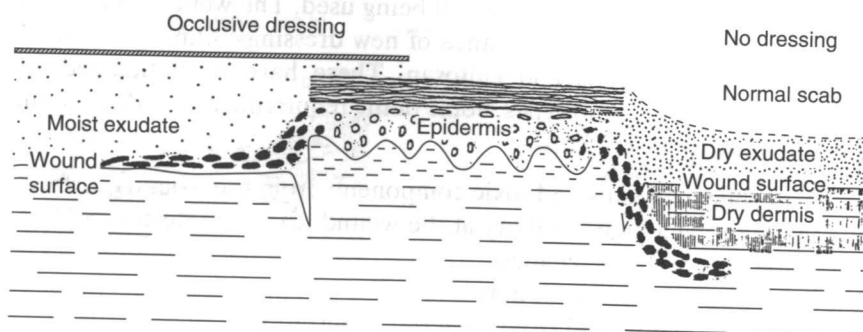
Properties that were added later include (1) having acceptable handling qualities, and (2) being sterilizable and comfortable.⁹ Having acceptable handling qualities means that product will not tear easily and disintegrate into wound.

3.6.2 Case for moist environment

The most significant advance in wound care resulted from the work of Winter¹ which showed that the occluded wounds, i.e. those in a moist environment, healed faster than the dry wound. An open wound, which is exposed to air, dehydrates and results in the formation of a scab or a scar. The latter forms a mechanical barrier against migrating epidermal cells, causing them to move through a deeper level of tissue, retarding healing (Fig. 3.3¹⁸). A moist environment prevents the formation of scab and allows the cells to move unhampered.¹⁹ If exudate is present, such as from an ulcer, it should be absorbed by the dressing, so that it does not solidify in the wound.

3.6.3 Dynamic nature and requirements

Each wound is different from any other even on the same individual, occurring because of the same reason, and in about the same region. Although it may fall in a given category, it still itself remains unique. This is because a wound is influenced by so many variables within the host and the environment that each will act independent of all others.²⁰ This is exacerbated by the facts that both the wounds and the hosts are dynamic and constantly change. Thus, there is the ongoing challenge faced in selecting the wound care dressing at each stage for each different person, and this requires a frequent reassessment of the lesion. Surgical wound assessment is an ongoing nursing responsibility that should be conducted every time a



3.3 Healing under a moist environment.¹⁸

dressing is changed, until the healing is complete. Assessment tools are available that determine the following aspects:^{21,22}

- Type of wound – superficial or cavity.
- Age of wound – fresh, days, weeks, dehiscent (split along a natural line).
- Stage of healing – granulating, epithelializing.
- Progress of wound – healing, deteriorating, become necrotic, infected or static.

3.6.4 General classification

Broadly, dressings may be classified as (1) passive, (2) interactive, and (3) bioactive, based on the nature of dressing action required. However, as illustrated above, the concept of wound occlusion to promote moist healing has probably impacted dressing design as much as any other development over the last thirty years. Wound occlusion does require careful regulation of the moisture balance at the site with vapor permeability helping the dressing to stay within its absorption limit. Thus, occlusive dressing types have been developed depending on the nature of the wound and the accompanying exudate. The theory of moist wound healing has led to approximately eight or nine separate types of materials and devices (Table 3.1), useful for different treatment indications. Each material type that represents these distinct groups has molecular and mechanical characteristics that confer properties to promote healing under specifically defined clinical indications. For example, it has been recommended that wounds with minimal to mild exudate be dressed with hydrocolloid, polyurethane, and saline gauze, and wounds with moderate to heavy exudate be dressed with alginate dressings. Dressings may also be selected based on wound tissue color, infection, and pressure ulcer grade.²³

When taken together, the combined properties of the dressing materials given in Table 3.1 would constitute an ideal dressing. Improvements in dressings that function at the molecular or cellular level to accelerate healing or monitor wound function are included among the ideal characteristics and may be termed interactive and intelligent materials, respectively. For example, a dressing that removes harmful proteases from the wound to enhance cell proliferation is an example of an interactive product. A dressing having a detection device in the material signaling 'time-to-change,' because the material has reached its capacity for deleterious protein levels, or reached a pH or temperature imbalance, may be termed 'intelligent'. Currently, there is not a universal dressing that will work for all wound types. Therefore, a dressing for a wound should be chosen on a case by case basis. When choosing a product, there are several factors to

Table 3.1 Classes of occlusive wound dressings with a description of their properties, clinical indications, and contraindications

Dressing and fiber type	Description	Properties	Indications
Thin films	Semipermeable, polyurethane membrane with acrylic adhesive	Permeable to water and oxygen providing a moist environment	Minor burns, pressure areas, donor sites, post-operative wounds
Sheet hydrogels	Solid, non-adhesive gel sheets that consist of a network of cross-linked, hydrophilic polymers which can absorb large amounts of water without dissolving or losing structural integrity. Thus, they have a fixed shape.	Carrier for topical medications. Absorbs its own weight of wound exudate. Permeable to water vapor, and oxygen, but not to water and bacteria. Wound visualization	Light to moderately exudative wounds. Autolytic debridement of wounds. Stage II and III pressure sores.
Hydrocolloids	Semipermeable polyurethane film in the form of solid wafers; contain hydroactive particles as sodium carboxymethyl cellulose which swells with exudate or forms a gel.	Impermeable to exudate, microorganisms, and oxygen. Moist conditions produced promote epithelialization	Shallow or superficial wound with minimal to moderate exudate.
Semipermeable foam	Soft, open cell, hydrophobic, polyurethane foam sheet 6–8 mm thick. Cells of the foam are designed to absorb liquid by capillary action.	Permeable to gases and water vapor, but not to aqueous solutions and exudate. Absorbs blood and tissue fluids while the aqueous component evaporates through the dressing. Cellular debris and proteinaceous material is trapped.	Used for leg and decubitus ulcers, sutured wounds, burns and donor sites.
Amorphous hydrogel	Similar in composition to sheet hydrogels in their polymer and water make-up. Amorphous gels are not crosslinked. They usually contain small quantities of added ingredients such as collagen, alginate, copper ions, peptides, and polysaccharides	Gels clear, yellowish, or blue from copper ions. Viscosity of the gel varies with body temperature. Available as tubes, foil packets, and impregnated gauze sponges	Used for full-thickness wounds to maintain hydration. It may be used on infected wound or as wound filler

Fillers	Calcium alginate which consists of an absorbent fibrous fleece with sodium and calcium salts of alginic acid (ratio 80:20). Dextranomer beads consist of circular beads, 0.1 to 0.3 mm in diameter, when dry. The bead is a three-dimensional crosslinked dextran, and long-chain polysaccharide	Heavily exuding wounds, including chronic wounds as leg ulcers, pressure sores, fungating carcinomas. Wounds containing soft yellow slough, including infected surgical or post-traumatic wounds	Heavily exuding wounds
Contact layer dressings (tulle gauze with petroleum jelly)	Greasy gauzes consisting of tulle gauze and petroleum jelly. Silicone-impregnated dressing sheet consists of an elastic transparent polyamide net impregnated with a medical-grade crosslinked silicone	The dressing which is porous non-absorbent and inert is designed to allow the passage of wound exudate for absorption by a secondary dressing	Shallow or superficial wounds with minimal to moderate exudate
Gauze packing	Cotton gauze used both as a primary and secondary wound dressing. Gauze is manufactured as bandages, sponges, tubular bandages and stockings. Improvement in low-linting and absorbent properties. Gauze is still a standard of care for chronic wounds	Cotton gauze may be wetted with saline solution to confer moist properties. Possesses a slight negative charge, which facilitates uptake of cationic proteases. Absorbent and elastic for mobile body surfaces	For chronic wounds it fills deep wound defects and is useful over wound gel to maintain moist wound; needs to be packed lightly. May traumatize wound if allowed to dry
Wound vacuum assisted closure	Polyurethane foam accompanied by vacuum negative pressure in the wound bed	Wound filled with foam and sealed with a film. Vacuum is obtained over wound	Deep wound to stimulate the growth of granulation tissue

consider, such as: (1) location, (2) size, (3) wound depth, (4) exudates amount, (5) infection, (6) frequency and difficulty of dressing change, (7) cost, and (8) comfort.

Traditional products like gauze and tulle that account for the largest market segment are passive products. Interactive materials composed of polymeric film products are mostly transparent, permeable to water vapor and oxygen but impermeable to bacteria. These film products are recommended for low exuding wounds. Bioactive dressings are ones that deliver substances active for wound healing; either by delivery of bioactive compounds or the dressing is constructed from a material having endogenous activity. These materials include proteoglycans, collagen, non-collagenous proteins, alginates or chitosan.

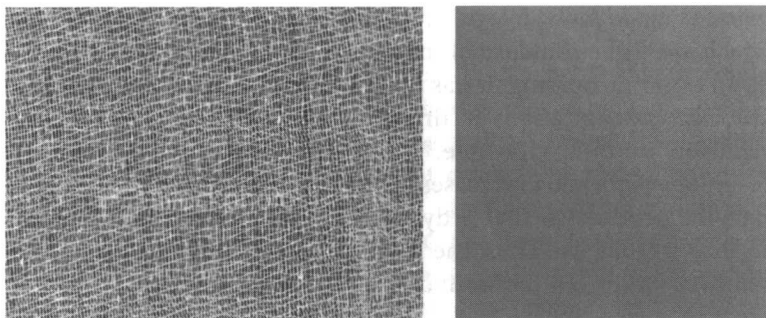
3.7 Types of dressings available

The range of dressing products is so large that there is potential for confusion when deciding which one to use. No single product is suitable for all types of wound and, when deciding which dressing to use, it is important to assess the wound and the stage of healing. Specific objectives must be identified; for example, if a wound is sloughy, the prime objective will be to de-slough by absorbing exudate; if the wound is clean and granulating, the aim will be to provide a moist environment to aid in healing. If the wound has a large cavity, it must be plugged. Based on considerations such as these, the available range of wound care materials can be described as below.²⁴⁻²⁸

3.7.1 Gauze dressings

A gauze is a traditional dressing and is still one of the most widely used product. In general, it is used for many purposes: skin preparation, cleansing, wiping, absorption, and protection. It can be either woven or non-woven. Cellulose fibers (cotton and rayon) are the typical materials used in making gauze. Synthetic fibers, in particular polyester, are also employed to modify properties and reduce cost. If woven, the pattern used is plain but it can vary from loose to tight. The non-woven dressings are highly homogeneous and soft. Figure 3.4 shows a comparison between a woven gauze and a non-woven sponge.

Gauze comes in pad, strip, roll, and ribbon form and is easy to handle; it packs easily which makes it a good choice when the wound is located in hard to reach areas. Gauze can be dry, moist, or impregnated. There are some disadvantages associated with the use of gauze: it is not a good thermal insulator and, when removed, it can cause damage to the wound. The damage occurs because the fibers of the gauze get embedded into the wound exudates and when removed it often peels off some of the newly



3.4 Woven and non-woven gauze.²⁹

formed epithelium. Impregnation of the fabric in a suitable compound alleviates this difficulty.

Dry gauze

Dry gauze, which is perhaps the most widely used material in home care, is used as a cover, as a means to prevent contamination, or to trap and lessen exudate. It is used as a primary absorbent dressing on a wound with a high amount of exudate. It is also used on closed wounds to prevent infection or additional trauma. The main problem encountered with gauze is that it tends to adhere to the wound and when removed from a large lesion may pull some of the newly formed tissues with it. If not being used for mechanical debridement as described below, it should be moistened before removal if it appears to be dry and adherent to the wound.

Moist gauze

This type of product is used to help maintain a moist environment and most often to promote granulation or protect a granulating wound, which is one of the first visual signs of healing.³⁰ It has been noted that 'wet-to-dry' and 'wet-to-moist' gauze dressings are often used in practice in a way that makes them indistinguishable.³¹ In fact, it should be noted, they have two different end purposes. Wet-to-dry dressings have been traditionally used as a means of mechanical debridement. The Agency for Healthcare Research and Quality has promoted the use of these for the debridement function. However, there are a variety of alternative methods for debridement, for example surgical debridement (when such is possible) and debridement using proteases, including collagenase-based and papain/urea-based formulations. The wet-to-dry gauze method for mechanical debridement is a controversial method as it is known to cause pain to the patient on removal. On the other hand, the wet-to-moist gauze is used for creating moist wound healing. For treatment of open ulcerating wounds,

gauze is made moist by soaking in normal saline. Normal saline dressings, which are still a standard of in-home and nursing home care, appear to act as an osmotic dressing. It has been shown that the osmolarity, sodium and chloride concentrations in dressings, placed on chronic wounds, remain relatively isotonic with time. The reason for this is that the dressing as a result of evaporation increases its tonicity. This draws fluid from the wound into the product so that a dynamic equilibrium occurs and the dressing regains isotonicity. Thus, the dressing remains functional for as long as it removes fluid from the wound.

Impregnated gauze

Further work has been done to fix the limitations of gauze by impregnating it with substances that promote wound healing. Substances currently used include; hydrogels, saline, and antimicrobial agents, as well as a wide variety of other materials, including paraffin wax. One such gauze, known for its vast improvement, is referred to as 'Smart Gauze', and has been found to be both super-absorbent as well as non-adherent to the tissue. Both the moist and the impregnated gauzes fall into the category of advanced occlusive dressings.

3.7.2 Impregnated dressings

With the work of Lister in 1867, in which bandages were impregnated with carbolic acid, the use of antiseptic treatment arose, and, shortly thereafter, Joseph Gamgee produced the first composite product containing cotton or viscose fiber medicated with iodine.³² Some of these dressings are still in use. These materials include gauzes and non-woven sponges, ropes and strips saturated with either saline, hydrogel, or other wound-healing promoting compounds, including peptides, polysaccharides, alginate, copper ions, and collagen. They are non-adherent and require a secondary dressing.

3.7.3 Transparent film dressings

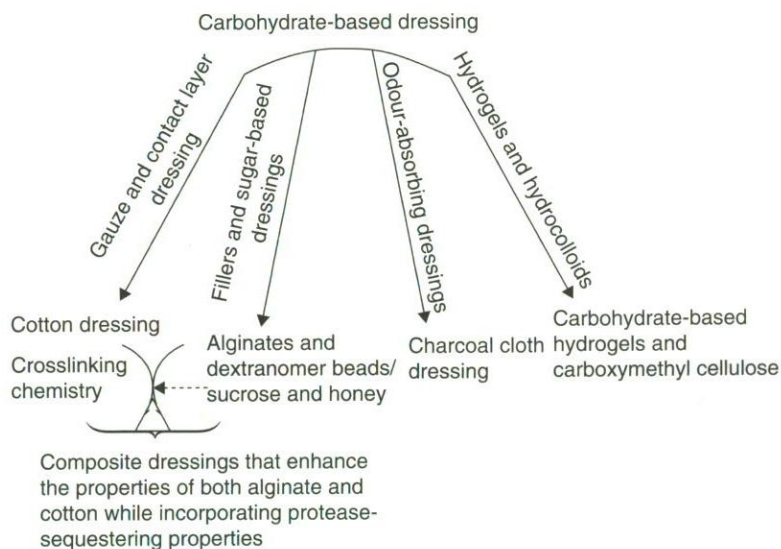
Films are homogeneous materials, which come in different thicknesses and consist of a polymer sheet that has one adhesive side. Film dressings are acceptable coverings for superficial wounds; being impermeable to liquids, water and bacteria, but permeable to moisture vapor and atmospheric gases, makes them suitable for use as occlusive structures. Because of their transparent nature, the films facilitate visual inspection without having to remove the dressing. They are applied to partial thickness wounds with very little or no exudate. They are also used to manage intravenous (IV) sites, lacerations, abrasions and second-degree burns.

3.7.4 Composite dressings

These dressings combine physically different components into a single product and provide multiple functions, such as bacterial barrier, absorption, and adhesion. The dressings, comprising multiple layers, have a semi-adherent or non-adherent contact layer that covers the wound and may include an adhesive border. The inner is the contact layer that is designed to accept the fluid and allow it to pass into the layer above where it is absorbed and held. The outer most layer is designed for protection and to secure the dressing to the skin. They are used as primary or secondary dressing; the latter, for example, for daily applications of creams, ointments etc. An example of how different types of carbohydrate combinations, involving cellulose, alginate and other components, can be designed into composite dressings is shown in Fig. 3.5.

3.7.5 Biological dressings

In 1975, Rheinwald and Green³³ developed a method that made it possible to cultivate human keratinocytes so that a 1–2 cm² keratinocyte cultured graft could be generated in about 3 weeks. This work paved the way for the eventual development of skin substitutes and biomaterials with wound interactive properties and biological activity, which have progressed



3.5 Various materials from carbohydrate sources present in wound dressings may be combined to form composite dressings with enhanced properties.

from the mid-1990s through the present. Biological dressings are derived from a natural source. Collagen dressings, derived from bovine, porcine, or avian sources, fall in this group. All these products are meant to accelerate healing. The biological dressings are available in many forms, including gels, solutions or semi-permeable sheets. While gels and solutions can be applied directly to the wound surface and covered with a secondary dressing, the sheet form can be simply used as a membrane and left in place for undisturbed healing. Biological dressings are indicated to be used for partial thickness wounds such as burns, abrasions, donor sites, skin tears, etc.

Skin substitutes that also fall under this category are being increasingly used. These contain both cellular and acellular components that appear to release or stimulate important cytokines and growth factors that have been shown to be associated with accelerated healing.³⁴ Some basic materials may also play a role in up-regulating growth factor and cytokine production and blocking destructive proteolysis. In this regard, the biochemical and cellular interactions that greatly promote healing have only recently been elucidated for some of the occlusive dressings described in Table 3.1. Some carbohydrate-based dressings stimulate growth factors and cytokine production. For example, certain types of alginate dressings have been shown to activate human macrophages to secrete pro-inflammatory cytokines.³⁵ Interactive dressing materials may also be designed with the purpose of either entrapping or sequestering molecules from the wound bed and removing the components responsible for deleterious activity from it as the product is removed, or stimulating the production of beneficial growth factors and cytokines through unique material properties. They may also be employed to improve recombinant growth factor applications. The impetus for material design of these dressings derives from advances in the understanding of the cellular and biochemical mechanisms underlying healing. With the knowledge of the interaction of cytokines, growth factors and proteases in acute and chronic wounds,³⁵⁻³⁸ the molecular modes of action have been elucidated for dressing designs as balancing the biochemical events of inflammation. The use of polysaccharides, collagen, and synthetic polymers in the design of new fibrous materials that optimize wound healing at the molecular level has stimulated research on dressing material interaction with wound cytokines,³⁴ growth factors,³⁹⁻⁴¹ proteases,⁴²⁻⁴⁵ reactive oxygen species,⁴⁶ and extracellular matrix proteins.⁴⁵

3.7.6 Absorptive dressings

Absorptive dressings are usually multilayer wound dressings which provide either a semi-adherent quality or a non-adherent layer. They are combined with highly absorptive layers of fibers such as cotton, rayon, etc. These

dressings are designed in a way so as to minimize its adherence to the wound so that the secondary trauma is as less as possible. These dressings are generally used as primary or secondary dressings for surgical incisions, lacerations, abrasions, burns, skin grafts or any draining wound.

3.7.7 Alginate dressings

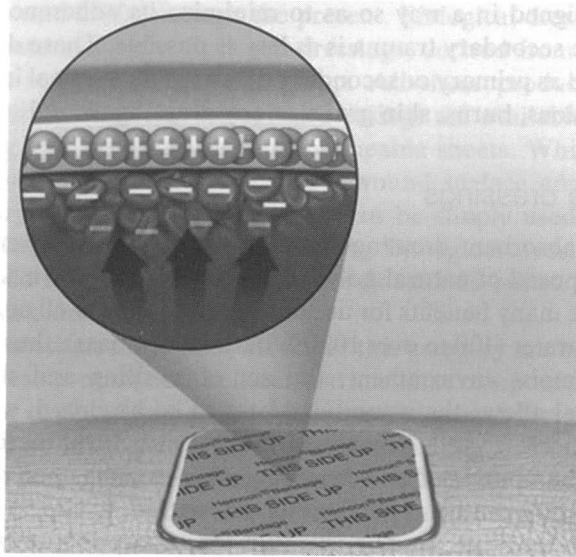
These advanced absorbent dressings are non-woven, non-adherent, pads and ribbons composed of natural polymers derived from brown seaweed. Alginates provide many benefits for use as dressings: they swell and retain large amounts of water (100 to over 1000% of their dry mass), thus providing an optimal moist environment; the act of swelling and diffusion throughout the gel allows the wound exudates to be absorbed, which, in turn, speeds up healing; and, because of the wet structure, the dressing does not stick to the wound bed and cause secondary trauma upon removal. The alginate dressing can be applied either pre-wetted, to supply a desiccated wound with moisture, or dry, to aid in the absorption of exudates. They must, however, be used with a secondary dressing.

As for the mechanism, when a dry mass of the material is applied to the site, it begins to absorb exudates during which a reversal in the ion-exchange process (from calcium ion in the dressing to sodium ions in the blood and exudates) occurs. This transforms the water-insoluble calcium alginate into water-soluble sodium alginate, thus absorbing a large amount of fluid.⁴⁷ The moist gel formed fills and covers the wound. The process is also said to make the dressing an excellent hemostatic agent, thus promoting clotting.⁴⁸

For dressings, alginates are made as ropes for packing deep wounds and as sheets for treating shallow wounds. Alginate dressings act as a antimicrobial by absorbing micro-organism-infected exudates, which are then removed when the dressing is changed.⁴⁷

3.7.8 Chitosan dressings

Chitosan is well known for its haemostatic properties and its bacteriostatic and fungistatic behaviors, all of which are particularly useful for wound treatment. As a haemostat, chitosan helps in natural blood clotting and in blocking of nerve endings, thereby reducing pain. The polymer gradually depolymerizes to release *N*-acetyl- β -D-glucosamine, which initiates fibroblast proliferation, helps in ordered collagen deposition, and stimulates an increased level of natural hyaluronic acid synthesis at the wound site. These processes aid in increased wound healing and decreased scar formation. Figure 3.6 gives a schematic representation of the mechanism by which chitosan works. It shows that chitosan, which is a polymeric amine, becomes



3.6 Haemostatic properties of chitosan.⁴⁹

positively charged when wet and attracts the negatively charged ions in blood and exudates.⁴⁹ Such attraction allows the material to clot blood quickly and also to act as an antibacterial agent on account of it attracting the negatively charged particles, including bacteria (Fig. 3.6), which are then removed at the dressing change.⁴⁷

An increase in healing rate of as much as 75% has been reported.⁴⁸ Because of the similarities in the chemical structures between chitosan and cellulose, the two are frequently mixed at both the polymer and the fiber levels. Such blending allows a manufacturer to engineer products with desired properties at lower cost. An example of a commercial product is 25% chitosan and 75% rayon. The improved fiber properties obtained allow the material to be converted into dressing by knitting, weaving or one of the available non-woven processes or by casting the polymer into a film. The functionality of the polymer also allows it to have built-in compounds that provide additional antimicrobial, and even deodorizing, characteristics.⁵⁰

One of the heaviest uses of chitosan is in making dressings for use by military in the combat zone. The claim of a product is that it will bond with the blood in 1 to 5 min and will also form an adhesive-type structure to protect the wound until access to a medical facility becomes available. Such quick response is needed in managing combat related injuries, as nearly 80% of all battlefield deaths result from bleeding in less than 10 min.⁴⁹ More specifically, chitosan has been developed as a sponge for use in controlling lethal extremity arterial hemorrhages in arteries.⁵¹

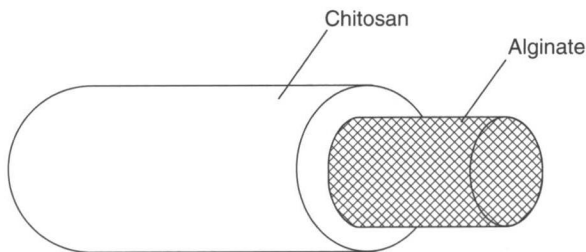
Chitosan is among a number of currently deployed haemostatic agents used within the armed services and has recently been contrasted with other materials for its efficacy in this application.^{52,53} Chitosan-based haemostatic products have also been compared with the more highly ordered crystalline structures of glycosaminoglycan materials⁵⁴ to learn more about the relative roles that carbohydrate structure and charge play in eliciting haemostatic activity. In addition to its use in fabric or film form, the material may also be incorporated into dressings in the form of powder and beads, and it has been grafted onto cotton to study its antimicrobial and haemostatic activities.

3.7.9 Chitosan/alginate bicomponent fiber dressings

Some wound products even combine chitosan and alginate to form a fiber.⁵⁵ With these bicomponent fibers (Fig. 3.7⁵⁶), the positively charged chitosan on the outside attracts the negatively charged microbes on the skin, promoting antimicrobial activity. The alginate polymer inside is still able to absorb the exudates. Thus, a non-toxic, biocompatible, absorbent and antimicrobial wound dressing could be made that combined the best attributes from both polymers to generate a faster healing product for large exuding wounds.

3.7.10 Hydrocolloid dressings

Hydrocolloid dressings can have various compositions, but the most common composition has a backing (outer layer) of either a vapor-permeable film or thin sheet of foam on which a mixture of sodium carboxymethyl cellulose, elastomers, adhesives and gelling agents are coated. Once the dressing is fixed on the wound, the warmth softens the lining of the dressing providing a gel cover for the wound bed. Hydrocolloid dressings are able to absorb a minimal amount of wound exudate and once its capacity is reached the remainder may leak out from under the dressing, termed 'strike-through'. The strike-through can be fast and,



3.7 Core-sheath alginate/chitosan.⁵⁶

therefore, these dressings are best suited for rehydrating dry black/brown necrotic tissues and wounds containing dry yellow slough. The hydrocolloid dressings are available in many shapes and some also have an additional adhesive border to prevent leakage or sliding of the dressing over the wound.

3.7.11 Hydrogel dressings

There are two types of hydrogel dressings.

Amorphous gels

Amorphous gels donate moisture to a dry wound and are, therefore, used for rehydrating dry necrotic or sloughy tissues and keeping granulation tissues moist – in much the same way as do the hydrocolloids. If the wound is sloughy and wet, this dressing will not be suited for the application. The amorphous gels come in a variety of forms and some have hydrocolloid or alginate added in an attempt to make them better at debriding or coping with wet wounds. The amorphous gels require a secondary dressing, usually a vapor-permeable film. The viscosity of amorphous hydrogels contributes to its function, and its ability to maintain integrity after absorbing wound fluid determines its role in moist wound healing. Less viscous types liquify after absorbing small amounts of exudate, and thereby add fluid to the wound. The more viscous types, on the other hand, maintain their structure and form a protective barrier over the site, thereby sequestering wound fluid and increasing the bioavailability of the exudate constituents, including proteases, for autolytic debridement and wound repair.

Non-amorphous gels

The non-amorphous gels provide a moist interface at the wound bed but do not donate as much water as do the amorphous gels and are, therefore, not the first choice for rehydrating a wound. However, they do provide a moist cover for granulating wounds. They are very soothing to wounds, making the dressings particularly suitable for use on superficial burns, including those caused by radiotherapy reactions. As they are gentle on removal, they are also suitable for use on easily damaged skin. The sheet gels come in adhesive and non-adhesive versions.

Foam dressings

Foam dressings usually consist of coatings of foamed solutions of polymers on sheets. The foam has small and open cells capable of holding fluids. Their absorption capacity depends on the thickness of the layer, and the material. Foams are permeable to gases and water vapor, but not to aqueous

solutions and exudate. Foams absorb blood and tissue fluids while the aqueous component evaporates through the dressing. Cellular debris and proteinaceous material are trapped in the material. These dressings are generally used on partial and full thickness wounds.

3.7.12 Antimicrobial dressings

Almost any type of dressing, i.e. sponge, gauze, film, or absorptive, can be made to have antimicrobial properties by incorporating agents such as silver and iodine. Silver is easily incorporated into chitosan and alginate products, thus greatly enhances their antimicrobial protection for the wound. A unique benefit of using silver in dressing is that it is highly effective in minute amounts (~1 ppm).⁴⁷

3.7.13 Silicone dressing

These are atraumatic dressings (they do not cause trauma to newly formed tissue or tissue in the peri-wound area) based on soft silicones, which are a particular family of solid silicones, that are soft and tacky, and which, therefore, tend to adhere to dry surfaces. A silicone dressing consists of a contact layer that is coated with silicone. These materials are inert and their main attribute is that they can be removed from a sensitive wound without causing trauma. The exudates can also be absorbed but this is accomplished by using an absorbent dressing that is given a coating of silicone. These dressing are particularly recommended for use as the first-line prophylactic treatment against development of hypertrophic scar and keloid after surgery.⁵⁷

3.7.14 Categories based on the management of moisture

The dressings discussed above can be further grouped into three main types:¹⁶

Dressings that absorb exudates

Absorbent dressings have a very high capacity for holding fluid. Hence, for a wound generating high levels of exudate, absorbent dressings will require fewer changes within a set period of time. Two of the materials that can support this function are the alginate and the foam products.

Dressings that maintain hydration

As a wound heals more, its exudate generation becomes less. This is when the wound starts to granulate or fill in with new connective tissue. When exudate levels decrease, it is not advisable to use absorbent dressings as

they may result in the dehydration of the tissues. In such a situation, all that is required is to maintain the hydration level. The hydrocolloid and the film products are suited for this application.

Dressings that donate moisture

When wounds are completely dry, they become covered by a layer of dead tissue, which needs to be removed to allow the wound to heal optimally. Often such tissues are removed by autolysis debridement which is slow digestion of the dead cells by enzymes. In such cases, maintaining a moist environment helps the process. The dressing should actively add moisture to the wound, and this is best performed by a hydrogel material.

3.8 Bandages

The functions of bandages are to (1) hold a dressing in place, (2) apply compression in some applications, such as to arrest bleeding in heavily hemorrhaging wounds or to treat varicose vein or leg ulcers, (3) immobilize fractures, (4) tie anesthetic tubes, and (5) hold cuffs, masks and other parts of textiles worn by a medical person for personal protection, safety or ease of mobility. Commonly, bandages performing a load-bearing function are made up of knitted or woven textiles, some containing elastomeric threads for required stretch and recovery force. Many types of products are available, including relatively inextensible, highly extensible, adhesive/cohesive, tubular, and medicated paste bandages.⁵⁸

The non-extensible bandages, essentially woven with open weave for breathability and low weight, are used for holding an absorbent pad or dressing in place at sites where stretch is not required, for example finger, arm or lower leg, tying anesthetic tubes and drains in position, and holding up a surgeon's trousers.

The extensible bandages are used for retaining a dressing and applying compression for control of edema and swelling in the treatment of venous disorders of the lower limb. The bandage should keep the dressing in close contact with the wound, and not inhibit movement or exert significant pressure that causes pain or restricts blood flow.

The compression dressing falls in a class by itself and is used primarily for treatment of varicose vein ailment. The optimum pressure needed varies with condition and place on the leg. The highest pressure is required at the ankle and the lowest on the upper thigh. Stockings in different sizes and having various mechanical properties are now available to fit a range of patients and provide gradient pressures of magnitudes suited for different specific categories of venous disorders. The pressures used are as low

as 14 and as high as 40 mm Hg. Mathematical analysis gives the bandage pressure P (Pa) on the surface as a function of the bandage tension T (N)—itself a function of the extension and the elastic modulus—, the radius of curvature of the limb R (m) and the width of the bandage W (m) as:

$$P = \frac{T}{RW} \quad [3.1]$$

As the effects of superimposed layers are additive, a configuration involving two turns of a bandage will essentially double the pressure. Because the bandage pressure is inversely proportional to R , wrapping a bandage at a given tension T will give the highest pressure at the ankle, where R is lowest, medium pressure at the calf, and the lowest pressure at the thigh.

Adhesive bandages are made of woven cotton or rayon fabric that is coated with a suitable adhesive. Highly twisted or crepe yarns in warp provide a degree of stretch and elasticity to the bandage that can serve as a structure for treatment of varicose veins and for immobilizing orthopedic fractures resulting from sport and other injuries.

Cohesive bandages combine some of the characteristics of ordinary stretch bandage with those of adhesive products. Whilst they do not adhere to the skin, a special coating on the surface enables layers to adhere to each other, thus preventing slippage and untying during use, including sports activity.

The simplest form of a tubular bandage consists of a knitted tube of a lightweight fabric. These are used under orthopedic casts, or placed over arms or legs that are covered with a medication.

In summary, it is clear that bandages are more directly textile structures that supplement dressings in treatment of wounds, both external and internal.

3.9 Materials used in dressings and bandages

A number of polymeric materials are used as films, fibers and other structures for developing wound-dressing products. Some of the primary materials employed are cotton, rayon, polyester, nylon, polyolefins, acrylic, polyurethane, chitosan and alginate. No doubt some other materials have been considered, for example recombinant silk, but for economic or technical reasons, they have either not passed beyond the experimental stage or are used in a limited way. A brief introduction to the chemical nature, the physical structure and the properties of the materials used in wound management products follows. An understanding of these can provide the manufacturer with a means of selecting the most appropriate material for a dressing for each different application.

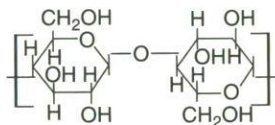
3.9.1 Cotton

The fiber that has been historically the most highly used in construction of dressings, absorbent pads, and bandages, is cotton, which still accounts for a significant volume of wound-care products in the world. The chemical structure of one repeat unit of the cellulose chain is shown in Fig. 3.8. Each repeat has three hydroxyl groups that are capable of linking with neighboring chains by hydrogen bonds. These groups, when free or weakly bonded, also attract and bond with water. The oxygen bridges between the repeat units allow chains to bend and twist, making the polymer flexible. The chains are quite long, and the fiber has over 60% crystalline structure. The most commonly used cotton in wound products is short (<2.5 cm). The cross-section is kidney bean shaped, i.e. relatively flat, but it becomes round when swollen with aqueous fluids. Once the waxes and impurities, normally present on raw fiber, are removed by a chemical scouring/bleaching step, the fiber surface becomes greatly hydrophilic and instantly wettable. Under ambient conditions, the material has a moisture regain (mass of water absorbed per dry mass of fiber, expressed as percentage) of about 8%, but when soaked can take up to about 30% water and swell significantly. One unique characteristic of cotton that separates it from other fibers is that it becomes stronger when wet. This makes the fiber preferred for use in towels, pads, sponges, swabs and many other absorbent wound care and surgical products, where mechanical integrity along with absorption are important. With an abundance of functional groups on the chains, the structure can be chemically modified to incorporate additional hydrophilic groups to enhance the fiber's absorptive properties, or therapeutic agents for imparting antibacterial or healing characteristics. The highly absorbent carboxymethyl cellulose (CMC) is a cellulosic material (usually based on wood fibers) that has been grafted with groups such as acrylic acid and which allows the structure to swell enormously and absorb many times the fiber's weight in water.

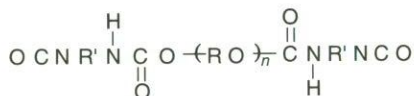
3.9.2 Rayon

The fiber, although chemically similar to cotton (Fig. 3.8), differs from it in physical structure: rayon's molecular weight is about one-fifth and crystallinity about one-half of that of cotton. These differences make rayon relatively weaker and more extensible, but more absorbent (about two times) than cotton. Thus, under ambient conditions, the fiber absorbs about 14% moisture, and when soaked, can swell and absorb almost 70% by weight water. The fiber, however, becomes significantly weaker when wet and, therefore, requires care when used directly on open wounds. One of the major applications of the fiber has been in disposable absorbent

Cellulose (cotton, rayon, lyocell)

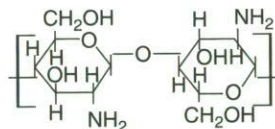


Elastomer

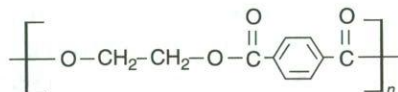
RO – aliphatic structure ($n \sim 10\text{--}30$)

R' – ring structure

Chitosan

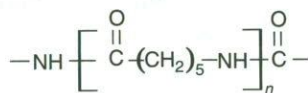


Polyester (PET)

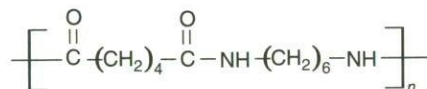


Polyamide

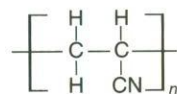
Nylon 6



Nylon 66

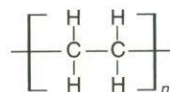


Polyacrylonitrile

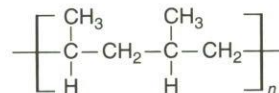


Polyolefin

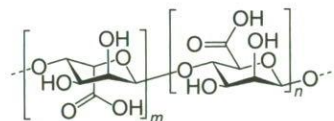
UHMWHD polyethylene



Polypropylene (iPP)



Alginic acid



3.8 Molecular structures of a fiber.

pads, sponges, and sanitary napkins. For use in absorbent dressings, usually a multilayer structure with rayon sandwiched between a permeable wound contact layer and an outer film layer is preferred. Being endowed by even more free functional groups than cotton, desirable compounds can be grafted readily to the material for specific uses.

3.9.3 Polyester

Polyester is one of the most versatile of the manufactured fibers that finds applications in many categories of textile products and is one of the widely used synthetic fibers in medical products. It is also the fiber frequently selected for combining with cotton and rayon in developing needled and spunlaced non-wovens for dressings. The chemical constitution of the commonly used material, poly(ethylene terephthalate) or PET, is shown in Fig. 3.8. The fiber has an aromatic component and an aliphatic sequence. Although the polymer lacks strong functional groups, the molecules, when drawn, pack closely and lead to a semi-crystalline mechanically strong and thermally stable fiber. Because of the lack of polar groups, the fiber has a low attraction for water (moisture regain ~0.4% under normal conditions); this makes the material largely hydrophobic. A number of variations of the basic repeat are available but they vary primarily in terms of the proportion of the aromatic and the aliphatic components and, as a result, lead to fibers with different physical and mechanical properties. Some low molecular weight aliphatic polyesters are used as low melt adhesives for binder applications. Aliphatic polyesters capable of hydrolytic degradation are also used in the manufacture of bioabsorbable products, in particular surgical sutures. The polymer can be melt-extruded both as a film and a fiber, the latter in different cross-sectional shapes and sizes to provide materials with various surface, physical, and mechanical properties.

3.9.4 Nylon

Although many different types of nylons can be produced, the two widely used are nylon 66 and nylon 6 (Fig. 3.8). The chains, being void of aromatic compounds, lead to fibers that have low modulus and high extensibility. The presence of amide groups in the chains, however, allows hydrogen bonding between NH and CO groups of adjacent chains; this gives the fiber excellent mechanical and thermal stability. The amide groups in the chains also attract water, thus making the fiber reasonably hydrophilic (moisture regain 4%) and wettable. Being one of the most stretchable and elastic of the common textile materials, in addition to being acceptably hydrophilic, nylon is a preferred material for the manufacture of tubular bandages and stretchable pressure hosiery for treatment of venous leg ulcers.

3.9.5 Polyolefins

The two materials of interest are polyethylene and polypropylene (Fig. 3.8). The one based on the simplest of the hydrocarbon polymers, polyethylene, can be produced in the extended form using the gel spinning process. This leads to the extended chain structures with ultra high modulus and tenacity (HMPE) suitable for use in many high-performance technical textiles. In the non-extended folded chain form, the polymer does not have adequate mechanical properties to lead to fibers, but the material can be made into flexible film or low melt adhesive or wax.

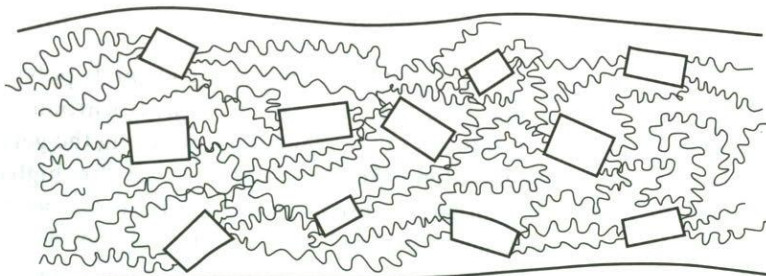
The second material is polypropylene which is also made into fiber and film. For making fibers, the chains must be in a stereo regular form. The olefin fibers have the lowest density ($0.91\text{--}0.96\text{ g cm}^{-3}$) of all fibrous materials. Both materials being strictly hydrocarbons are truly hydrophobic and, therefore, do not wet. They also have very low surface energy ($\sim 24\text{ mN m}^{-1}$), which, among textile polymers, is only higher than that for polytetrafluoroethylene ($\sim 12\text{ mN m}^{-1}$). Accordingly, olefins generally lead to low-adhesion film products, which are used for developing low-adhesion contact layers for dressings. The fibers also have low melting points ($<175^\circ\text{C}$), which vary with chain length and, in the case of polypropylene, with tacticity. Accordingly, olefins are frequently used as low-melt coatings on regular fibers or as binder fibers for making fabrics by the non-woven methods. In dressings, the polymer finds extensive use in the development of contact layer films.

3.9.6 Acrylic

The chemical structure of the basic polymer is illustrated in Fig. 3.8. The pendant acrylonitrile groups ($\text{C}\equiv\text{N}$) are highly polar and lead to extensive bonding between chains. Because of this, a second component, up to about 15% by weight, which is another vinyl monomer, e.g. methyl acrylate or vinyl acetate, is inserted into chains to improve polymer solubility for extrusion into fiber. The fiber, with only about 2% moisture regain, has limited interaction with aqueous fluids. A major attribute of the fiber that particularly suits its use in dressings is its naturally high resistance to colonization of micro-organisms.

3.9.7 Elastomeric fibers

The unique characteristic of elastomeric materials, whether used as shaped fibers or films, is that they are soft and highly stretchable and elastic. The synthetic elastomers are linear block copolymers containing soft amorphous sections that provide stretch and hard crystalline components that

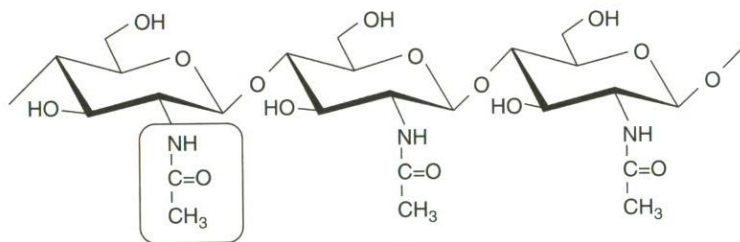


3.9 Illustration of fine structure in elastomeric fibers, composed of blocks of crystallizable hard segments and non-crystallizable coiled soft segments.

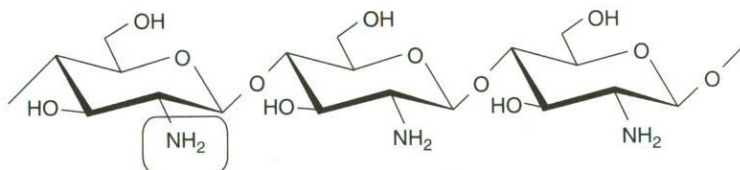
act as tie points and hold the structure together in a memory-endowed mechanically stable material. These polymers are usually known as the segmented polyurethanes, whose general chemical structure is given in Fig. 3.8. The hard segments of neighboring chains tend to associate with each other and crystallize, while the soft segments remain largely coiled and unassociated (Fig. 3.9). Stretch of the order of 100% or more is common. The material being elastic and having the ability to return back to its original shape and size, its major application is in developing products that are required to exert transverse pressure of the required level for treatment of skin disorders. Thus, using elastomeric fibers in a bandage, one can keep an absorbent dressing pressed on a puncture wound to stop bleeding, or in hosiery one can apply desired pressures on different parts of leg to treat venous disorders.

3.9.8 Chitosan

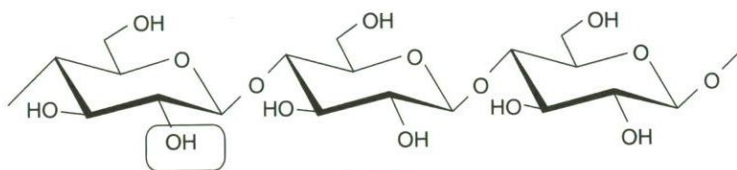
Chitosan is a natural biopolymer and is derived from chitin. The latter is the second most abundant natural polysaccharide on earth, with cellulose being the first. It is found in the shells of crabs, shrimps, prawns and other crustaceans. While chitin itself can be used in dressings, it is its deacetylated derivative chitosan that is used extensively in this application. Figure 3.10 shows the difference between chitin and chitosan, where the acetyl group is eliminated and replaced with an amino group.⁵⁹ The degree of substitution varies from product to product but is typically about 80%.⁶⁰ The modification makes the material a poly(β -(1-4)-2-amino-2-deoxy-D-glucopyranose), which is a polycationic biopolymer that is also found in some insects and species of fungi.⁴⁸ The deacetylation process provides open groups that cause the chemical and biochemical reactivity of chitosan to be relatively much greater and is one reason why



Chitin



Chitosan



Cellulose

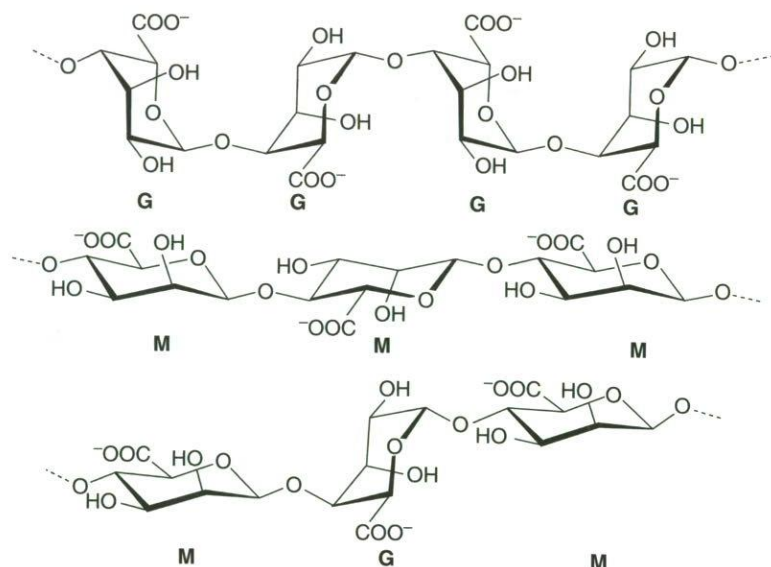
3.10 Chitin, chitosan and cellulose.

this form is used more frequently. Another reason is that chitosan is more soluble than chitin.

Chitosan-based composite films are gaining attention for their ability to stop bleeding in wounds and promote healing. Chitosan is biodegradable, biocompatible, non-toxic, and has great antibacterial properties. Its properties make it an excellent choice for many medical applications. As a fiber or film it is used for wound care, and, in microcapsule or bead form, it is utilized for drug delivery.⁶¹ For use as a film, that has some mechanical integrity, chitosan is mixed with another polymer.⁶²

3.9.9 Alginate

Alginate is a natural polysaccharide which is derived from brown seaweeds.⁶³⁻⁶⁵ It has been used for a variety of purposes, ranging from thickening agents in food, to pharmaceutical additives. It is a block copolymer made up of 1,4-linked β -D-mannuronic acid (M) and α -L-guluronic acid



3.11 Mannuronic (M) and guluronic (G) block structures in alginate polymers.⁶⁵

(G) residues (see Fig. 3.11 for stereochemical structures). There are three block structures present: M/M blocks, G/G blocks and M/G blocks. There are a variety of seaweeds that alginate is derived from and each species has a different composition of the acids. These result in a range of properties found in the material. Those containing a higher percentage of guluronic acid tend to be stronger and stiffer than the ones containing a higher percentage of the mannuronic acid. The latter, however, tend to have better swelling properties.

In order to achieve alginate fibers from seaweeds, sodium alginate must be extracted from crushed and washed raw material. The sodium alginate is soaked in water where a viscous solution is formed which is then extruded into a calcium chloride bath. In the process, the sodium ions are replaced by the calcium ions. After washing and drying of the gel, the insoluble calcium alginate fibers remain.⁶⁶ Webs containing the fibers may be composed by first airlaying or carding-cum-crosslapping and then needle punching, to make the dressing. Fibers may also be converted into knitted or woven fabrics or assembled in a rope form.

When the calcium alginate dressing is used on a wound, a reverse ion-exchange process takes place. The sodium ions in the blood and wound exudates are exchanged with the calcium ions in the alginates.⁶⁶ Moisture is necessary for the alginate dressings to work properly, which is why they will not be beneficial on dry wounds and are used mainly on heavily exuding wounds.

During production, other desired molecules can be introduced resulting in altered physical and chemical properties. For instance, silver, chitosan, and other antimicrobial molecules can be integrated either physically during fiber formation or chemically by grafting them onto the alginate chains.⁶⁷ Molecules are also frequently added to improve the mechanical properties of the dressing. The fibers produced can be processed to form a non-woven mesh by one of the methods available.

3.10 Textile processes involved in formation of dressings and bandages

3.10.1 Introduction

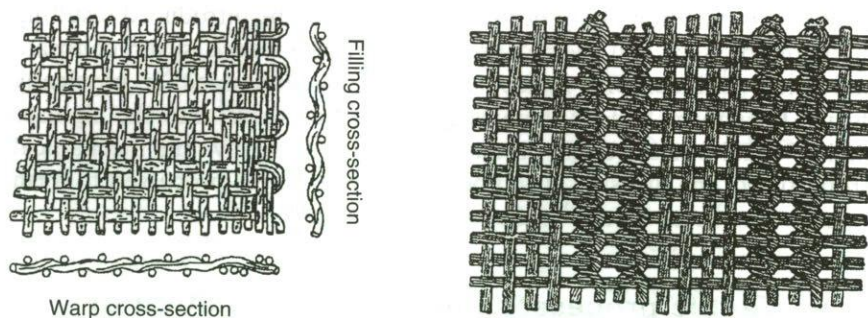
Dressings are made from polymers and fibers in a variety of types. The form in which these materials are used may be film, rope, ribbon or fabric. The latter are made by a weaving, knitting, braiding or a number of non-woven processes. Unless the product required is primarily load bearing, the fabric used is most likely the non-woven. The latter is usually soft and bulky and is porous and absorbent. Non-wovens are also homogeneous and most economical to produce. Films used as dressings are also non-wovens, but they are cast or extruded directly from polymer. These are thin and flexible but usually not as three-dimensionally drapeable and conformable as are the woven and the knitted fabrics. The same limitation also applies to the regular non-woven fabrics, i.e. they lack drape and conformability. A description of the methods of forming fabrics for dressings is given below. Since the non-woven fabrics are the largest used in forming dressing products and there are several technologies involved in making these fabrics, a more detailed description is presented of these processes and the structures made from them.

3.10.2 Yarns

Fibers or filaments obtained from extrusion of polymers are twisted (for short fibers) or entangled (for continuous filaments) to form a continuous thread that has mechanical integrity enough to support stresses imposed on them during their weaving, knitting, or braiding into fabrics. A typical short fiber or staple yarn will contain about 100 individual fibers in the cross-section and have a diameter of the order of 0.2 mm. These one-dimensional structures are therefore quite strong and flexible.

3.10.3 Woven fabrics

A significant fraction of gauze fabrics are based on woven structures. These fabrics are manufactured on a loom that has a running sheet of yarns,

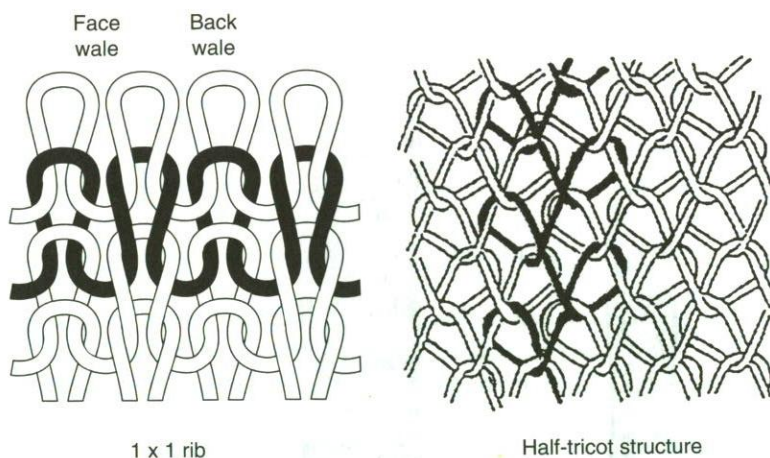


3.12 Plain weave and leno weave.

known as warp, within which are inserted cross-threads, known as weft, at right angles. The woven fabrics used in wound management applications have the simplest structure called plain weave, shown in Fig. 3.12. Woven fabrics are relatively inextensible but dimensionally very stable structures with porosity that can be varied from nearly zero value to very high value (gauze, cheese cloth). A major problem with the woven fabric is the tendency of threads to unravel at the cut edge. A special weave known as 'Leno' in which two warp threads twist around a weft reduces this tendency.⁶⁸

3.10.4 Knitted fabrics

Knitted fabrics are categorized as either 'weft' or 'warp' constructed. Of the two, the faster and the more economical to produce is the weft knitted fabric that can be accomplished with a single package of yarn. The warp knitting process, on the other hand, requires a warp beam, i.e. a running sheet of yarns as does the weaving process. Loops are formed transversely in the case of the weft knitting and essentially vertically in the case of the warp knitting (Fig. 3.13). Simplest or plain weft knits tend to be very extensible and dimensionally unstable. One could improve on these properties by using additional yarns that interlock the loops. In contrast, the warp knitted structures are basically more interlocked and dimensionally stable. The knitted fabrics are more flexible, compliant and conformable than the woven fabrics, and one of them, the warp, also does not unravel as easily when cut to fit an application. A major limitation of knitted fabrics in some applications is porosity which, owing to the nature of the loop structure, tends to be high. The knitted nets and bandages can be draped more effectively than woven materials over areas that require three-dimensional conformability. One of the primary applications of knitted structures in wound care is in compression hosiery used for treatment of venous stasis.



3.13 Weft knit and warp knit structures.

3.10.5 Braided fabrics

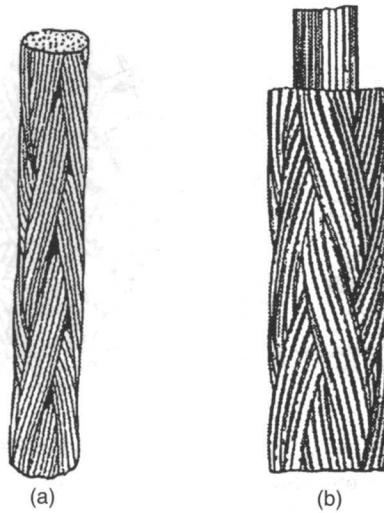
Although not used as extensively as the other two types in wound care, the braided fabrics are unique structures that are particularly suited for producing small diameter tubular and mechanically stable rope structures, the latter suitable for packing cavity wounds. The braids (Fig. 3.14) resemble woven fabrics except that the crisscrossing is not at right angle. One can have flat braids and tubular braids, the latter with and without a core. The braids are mechanically stable structures like the woven, but they are more flexible and conformable than the woven. The criss-crossing pattern in braids also leads to porosity.

3.10.6 Non-woven fabrics

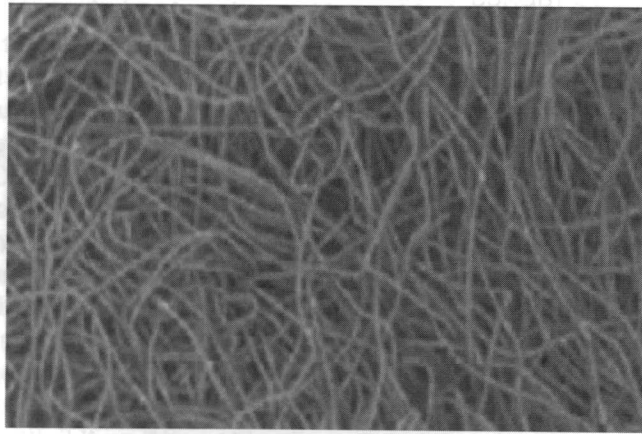
As a major function of dressings is to provide a soft and resilient hand, absorb and retain exudates, if present, and serve as a protective covering, non-woven structures suit the application and find extensive utilization in the products. Such structures have been used as the facing, as well as the entire absorbent pad of a wide variety of dressings.

These fabrics (Fig. 3.15) differ from woven and knitted in that the former are more homogeneous, softer, and more resilient, than the latter. The processes involved are also faster and more economical. A reason for the latter is that the fabric is made directly from the fibers, without the intermediate step involving the yarns, or even from the polymer itself.

Many different types of processes are involved in the manufacture of non-wovens used in wound care products. These lead to different structures



3.14 Braided structures a) without and b) with core.



3.15 Non-woven fabric.⁶⁹

and properties and, therefore, suit different functions of a dressing. Accordingly, it will be useful to include here an introduction to the different processes involved and the structures produced by them. Considering that there is a high similarity between the design of an advanced multi-layer composite dressing and an engineered absorbent sanitary product (napkin, diaper, or an incontinence pad), a highly relevant but detailed discussion of non-woven processes, structures produced by them, materials used in producing them, and the properties obtained, can be found in a chapter, titled 'non-wovens in absorbent materials,' by Gupta and Smith.⁷⁰

A non-woven fabric consists of a web based on fibers or fibrils. A binder may be incorporated to hold fibers more firmly and provide mechanical integrity and strength as required. The manner in which the fibers are assembled into a web and bonded has a profound effect on the web properties. A web structure can range from the extremes of a highly oriented fiber configuration produced by the carding process to one of completely random arrangement obtained from the air laying or spunbonding process. An intermediate arrangement obtained by cross-lapping can also be developed.

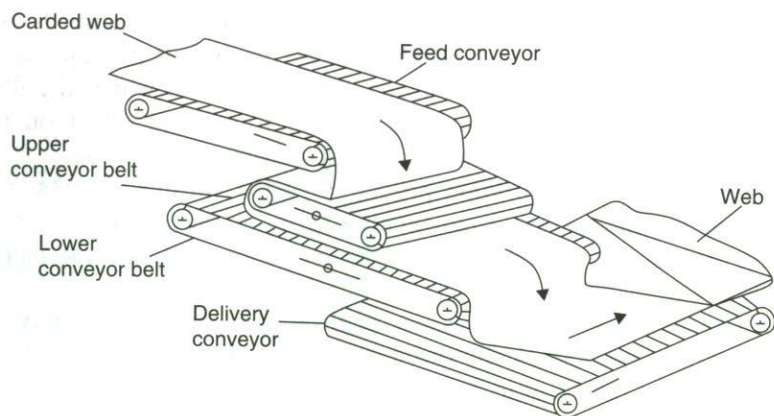
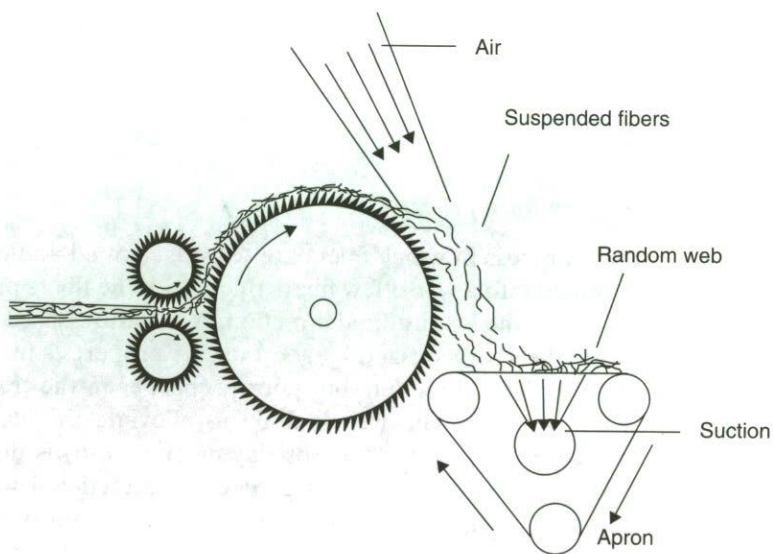
The bonding of fibers is accomplished either mechanically through entanglements, chemically through use of a binder, or thermally through melting and fusing, or using a combination of these methods. A non-woven web is generally considered 'finished' as soon as the fibers are assembled into an appropriate structure and bonded by one of the methods mentioned. It is possible, however, to give additional chemical or mechanical treatment to the bonded web, which can have an important influence on web characteristics. These include, as examples, a chemical repellent, wetting or antimicrobial treatment, and mechanical embossing, aperturing or glazing treatment.

Uni-directional dry form process

This is a carding process in which fibers are teased, combed and oriented by wires and formed into a web a few fibers thick, with the fibers predominantly oriented along the longitudinal direction. A structure based on such a web will usually be characterized by good tensile properties in the longitudinal or the machine direction, but poor properties in the transverse direction. Cross-lapping of the web is done to alleviate this deficiency and also to increase its weight. The cross-laying (Fig. 3.16) is done in a continuous manner, often onto another carded uni-directional web. The result is a fiber web with one layer having a uni-directional orientation in the machine direction and the other succeeding layers having a uni-directional web oriented at an angle close to but less than 90° to the machine direction. By proper selection and juxtaposition of the layers of different webs, it is possible to control the orientation in the final web.

Random laid or air laid process

In this process, individualized fibers are suspended into an air stream, and allowed to be deposited on a moving perforated belt or drum (Fig. 3.17). The web obtained has fibers distributed randomly. In addition to the typical textile length fibers (0.9–2 in.), very short wood pulp fibers (~0.3 in.) can also be used in this method. The process of deposition prompts some fibers

3.16 Carding cross-lapping process.⁷¹3.17 Random air laying process.⁷²

to be lifted out of the X - Y plane and become partially oriented in the Z direction. This results in a web having higher bulk and larger void volume, which enhances the web's fluid absorbing and holding capability.

Chemical and thermal bonding of webs

A bonding method frequently employed for the dry form web is chemical, involving an acrylic or a latex binder.⁷³ The proprietary formulation will include other ingredients as well, which are a catalyst (for cross-linking), a viscosity modifier, a defoaming agent, and a surfactant. The resin add-on

can vary over a wide range, but the typical value will lie in the 10–25% range. The binder can be applied by a variety of procedures, including saturation of fabric, spraying the web, or printing binder on the web with a roll. The saturation method is normally not considered for absorbent materials, as the binder covers essentially all fiber surfaces. Spray bonding with careful adjustment of parameters can provide bonding at just the cross-over points, leaving the rest of the web material largely binder free. The placement of the binder resin can be even more finely controlled by print bonding, in which the binder is positioned on the web in a discrete predetermined pattern utilizing engraved rolls⁷⁴ or a rotary screen. More recently, the use of binder in the form of foam has been utilized.⁷⁵ This leads to a reduction in the drying cost of the printed web, as the binder is diluted with air rather than water.

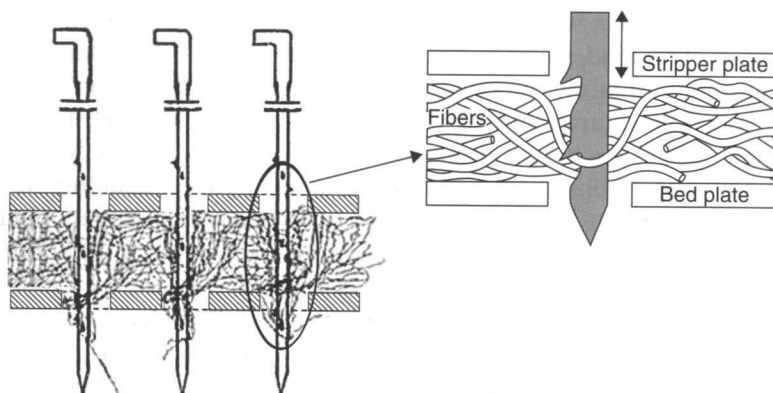
A modification of the bonding process has also been used, which is suited in particular for the contact layer of the dressing. This involves the use of thermal techniques for bonding.^{76,77} The fabric contains a blend of low melt fibers (polyethylene and polypropylene) and other fibers, natural or man-made, and is bonded with heat using engraved hot rolls. Another version of the thermal method involves the use of bicomponent fibers that have a higher melting core with a lower melting sheath. When heat is employed by embossed calendar rolls or by hot air, the sheath layers bond.

Spunbond process

A polymer melt is extruded through a large number of spinnerets to form numerous continuous filaments. These fall onto a moving conveyer and form a web by overlapping with each other. Fibers are oriented randomly, which is achieved by oscillating spinnerets, field-induced by electrical charges, and/or the controlled flow of air. Webs may be bonded by thermal or chemical means over their entire area to produce a thin, smooth, fabric. Such a structure is stiff, but bonding at strategic points can be used to produce a softer and more flexible fabric. The polymers used in spunbonding are mainly polyester, nylon and polypropylene. Although made from a hydrophobic polymer, the web having a high porosity lends itself to use as a wound contact layer. Print bonding used for dry form non-wovens can also be utilized in bonding these webs.⁷⁸ The amount of bonding area for a typical spunbond fabric ranges from about 10 to 35%.

Needlepunch process

In the needlepunch process, in which primarily the carded-cum-crosslapped or random laid webs are used, the bonding is achieved by the penetration of a set of barbed needles through the structure (Fig. 3.18). The barbs are designed such that, as a needle penetrates, groups



3.18 Needlepunch process with magnified view of the needling action.^{71,72}

of fibers from the top layer of the web are engaged and driven through the thickness of the web. As the needle retracts, the fibers are released from the one-way barbs. This results in mechanical entrapment and orientation of the portions of fibers in the thickness direction. By control of the needle penetration and the repetition of the needling action from the opposite side of the fabric, a three-dimensional, mechanically entangled network can be achieved.⁷⁹ The process tends to consolidate the web but creates oriented capillaries or channels along the thickness. This imparts resiliency to the web and the capability to efficiently imbibe and hold large volume of fluid. There is a minimum amount of fiber that is required for effective mechanical engagement. Consequently, most needle-felt structures have a weight of 60 g m^{-2} or more.

Wet laid process

The wet laid non-woven process bears a considerable resemblance to the paper manufacturing process. Short fibers (generally one-quarter inch or less) are suspended in an aqueous slurry along with minor amounts of other constituents. The slurry is subjected to strong agitation in order to cause the fibers to be uniformly distributed. The slurry is conveyed to a moving wire belt, where the liquid drains through and the fibers are left in the form of a mat in largely random configuration. The web is then removed from the conveyor, taken through a bonding process, dried and then wound up onto a roll.

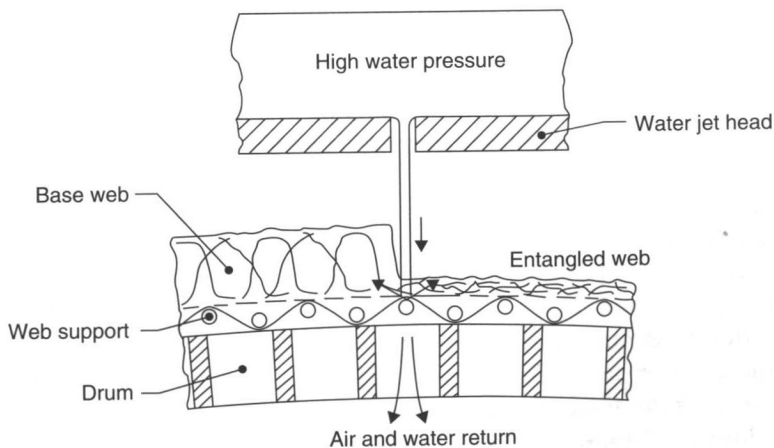
In paper manufacturing usually 100% pulp (~3 mm) is used and bonding by hydrogen linkages is extensive, which leads to the typical thin and stiff structure. In the wet laid non-woven process, on the other hand, compositions can range from sizeable wood pulp content to a completely synthetic

fiber furnish. Also, in these structures, usually the fibers used are longer and crimped or convoluted, and the frequency of bonding is lower. This leads to a fabric that is relatively bulkier and softer. If pulp is used as one of the constituents, its fraction and, therefore, the resulting hydrogen bonding, are small. An external binder is often employed to increase strength while maintaining bulk. Bonding is usually achieved by either the chemical or the thermal methods described earlier.

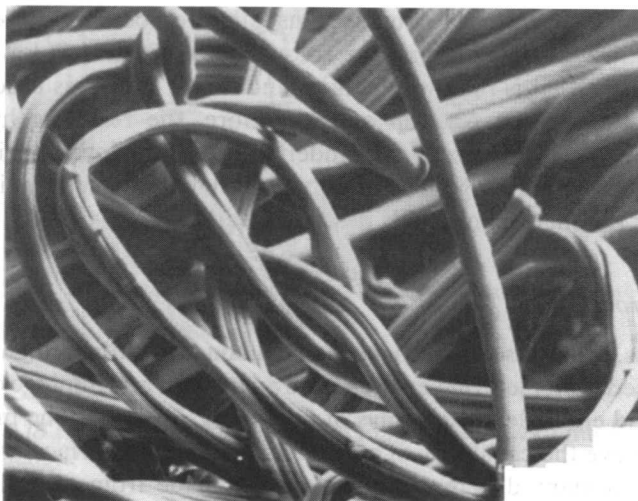
Spunlace process

This process, which also leads to mechanical bonding, utilizes high-energy, closely spaced, water jets that emerge from an injector and impinge on a web substrate and entangle loose arrays of fibers (Fig. 3.19).^{80,81} The process is claimed to have the capability of producing a variety of surface and fabric patterns from many different precursor webs made from essentially any fiber that is not too stiff or brittle to bend or move. Figure 3.20 shows a spunlaced web made from a blend of polyester and rayon fibers. The injectors are positioned above the moving backing belt or rotating drums, which are perforated and carry the unbonded web through the unit.^{82,83} The impaction of water jets forces fibers onto and into the backing belt, giving the fiber web surface the texture of the surface of the belt. If the backing belt has large holes, an apertured web is obtained; if it has very fine holes, a web approaching a non-apertured structure is obtained. This versatility associated with the configuration of the supporting belt provides the capability to produce a wide range of surface and structural features in a spunlace fabric.

Wood pulp/polyester fiber blended spunlace fabrics were originally the largest volume of products produced by the process; however, other



3.19 Spunlace process.⁷¹



3.20 Spunlace web from rayon and polyester.

spunlace fabric types have become significant commercial successes, including those based on 100% bleached cotton and its blend with synthetic fibers.

In addition to drylaid and wetlaid precursors, a direct-laid web from the spunbonding or meltblowing process has also been used, but usually as part of a multilayer construction. Composite fabrics have been produced by hydroentangling a drylaid or a wetlaid staple fiber web superimposed on a direct-laid fabric that serves as a reinforcing scrim.⁸⁴ This variant is especially useful in producing a composite of a lightweight spunbound fabric of olefin or polyester around whose filaments a wood pulp layer has been entangled. This can provide a strong yet absorbent fabric from relatively low-cost raw materials.

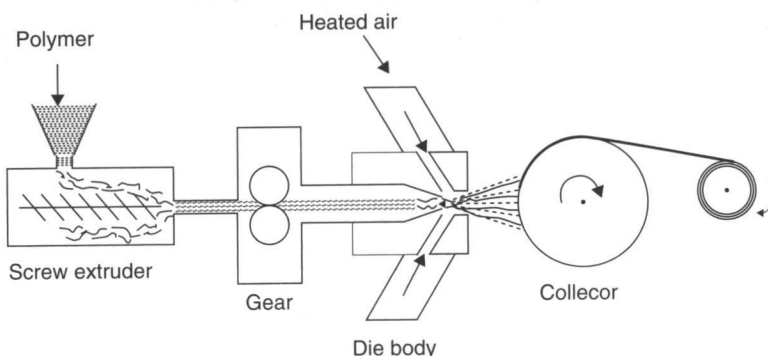
Modifications of the hydroentangling system have also been used. One such process involves fiber entanglement at a relatively low level, which is still sufficient to convey some mechanical integrity; this is then supplemented by a limited amount (1–5%) of external latex binder, which conveys additional strength and integrity to the structure.⁸⁵

In another modification, the low level of fiber entanglement is supplemented by adding a small amount (~15%) of thermoplastic binder fiber. After drying the fabric, additional heat is applied to melt and thus activate the latter. A polyolefin bicomponent fiber is used for this process, although other binder fibers can also be employed. This same technique, involving addition of a low melt fiber, is now used at times to enhance the physical properties of needle punched fabrics as well.

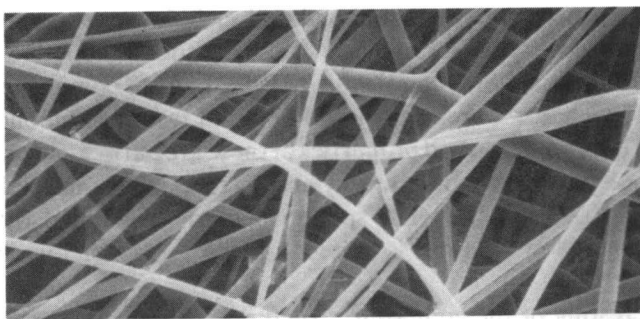
A vast majority of spunlace fabrics are produced in basic weights ranging from about 20 g m^{-2} to about 100 g m^{-2} . A web of weight less than 20 g m^{-2} does not develop enough integrity unless an auxiliary means of bonding or very low denier fibers providing high number of fibers are used. Webs weighing more than about 100 g m^{-2} are usually too heavy to be penetrated by water jets, unless very high energy levels are used.

Meltblown process

Meltblowing is a unique, one-step process in which the melt of a polymer emerging from orifices is blown into super fine fibers by hot, high-velocity air. A molten polymer is blown into ultrafine fibers and collected on a rotary drum or a forming belt with a vacuum underneath the surface to form a nonwoven web. Two hot air streams at near sonic velocity at the polymer exit attenuate the extruded stream of polymer (Fig. 3.21). A typical meltblown web contains fibers of a range of sizes (Fig. 3.22); however, typically, the fibers are $1\text{--}10 \mu\text{m}$ in diameter. The fibers are tacky and tend to stick to each other and take the shape of the apron or object on which they are collected. It is recognized that the fibers are weak



3.21 Schematic of a meltblowing process.



3.22 Micrograph of a meltblown fabric showing variable fiber size.⁸⁶

and the web lacks uniformity. This currently restricts the application of meltblown structures to non-load-bearing products. However, a meltblown web may be combined with a web made by another method and form a composite that not only has improved mechanical properties but also other desirable physical properties. Such products contain fibers of different types and sizes, which can lead to novel structures with properties not possible from a single material or process.⁸⁷

Although polypropylene has been the material used most widely, other polymers have also been used successfully, these being polyethylene, polyester, and nylon. Essentially, any thermoplastic polymer, including biodegradable, can be used.

Polymer web process

These processes essentially lead to sheet materials such as thin foams, plastic nets,^{82,88} perforated films,^{83,89} and similar materials. The methods of manufacturing these miscellaneous materials are as diverse as their natures. They frequently arise from modified plastic processing techniques and often represent the combination of technologies. In general, the products are not hydrophilic and, hence, not inherently absorbent. Because of their structure and characteristics, however, these materials can often substitute for a component of an absorbent product, including non-adherent contact layer and protective outer layer of a dressing.

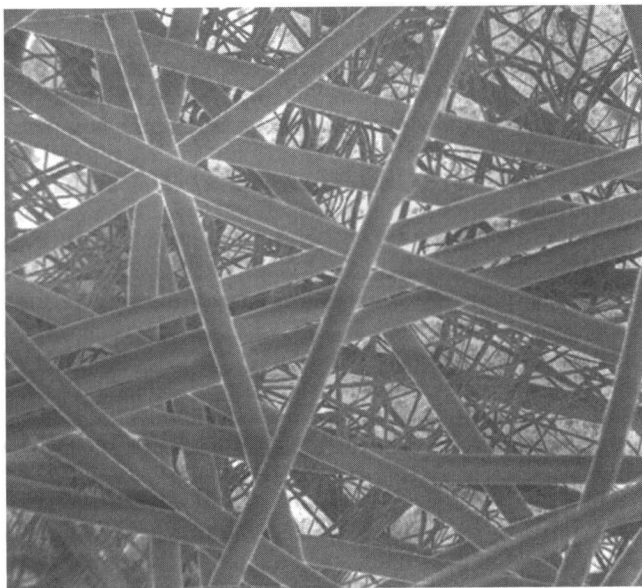
Advanced composites from combination of technologies

Attractive composites can be made by a combination of airlaid and spunlace processes. One example is infusing pulp by airlaying onto a regular cotton or rayon web during hydroentangling. Such a product has similar or superior absorbency of 100% cotton or rayon fabric but at a fraction of the cost. A typical blend for pulp and fiber will be 50/50. Such a structure can be used as the absorbent layer in a dressing.

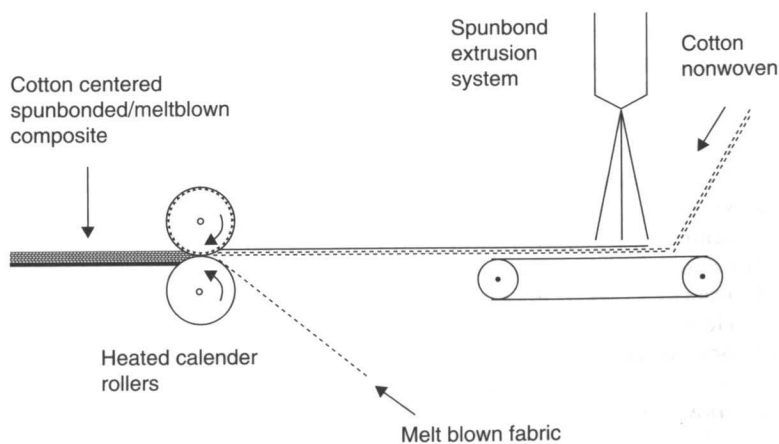
Another structure that has received great emphasis during the past two decades is one that combines spunbond and meltblown processes in producing a composite fabric. Examples of these are the spunbond (SB)/meltblown (MB), known as SM, and the SB/MB/SB or SMS composites. Often two layers of meltblown are sandwiched between two of spunbond to lead to SMMS. The production and properties of these are particularly enhanced by the use of polypropylene/polyethylene bicomponent materials in the preparation of MB webs.^{90,91} The spunbond fabric, combined with ultra-lightweight meltblown fabric, is suited for use as facing for absorbent products (Fig. 3.23).

Most interesting of the composite structures, however, that can lend to direct use as dressings, are the cellulose-centered non-wovens that are capable of being produced on an integrated line.^{70,92} These are laminates

that have cotton, or another cellulosic fiber web, sandwiched as a core between two layers of meltblown and/or spunbond webs, with the size and the characteristics of each of the three adjusted to suit the application. For developing such products, the absorbent material used could be cotton or rayon of regular length, fed from a pre-formed roll, or pulp of short length, deposited directly from an airlaying system on the site in coordination with the formation of the spunbond/meltblown webs (Fig. 3.24).



3.23 Micrograph of a polypropylene SMMS fabric.⁹¹



3.24 Preparation of cotton-centered composite with spunbond and meltblown webs forming the outer surfaces.

3.11 Acknowledgement

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